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Performance of Linear TDA-MAC in Full-Duplex Underwater Acoustic Chain Networks

Aliyu Ahmed, Paul D. Mitchell, *Senior Member, IEEE*, Yury Zakharov, *Senior Member, IEEE*, and Nils Morozs, *Member, IEEE*
Department of Electronics Engineering, University of York, UK.
Email:{aliyu.ahmed,paul.mitchell}@york.ac.uk, {yury.zakharov,nils.morozs}@york.ac.uk

***Abstract*—A study of Linear Transmit Delay Allocation MAC (LTDA-MAC) in full-duplex Underwater Acoustic Chain Networks (UACNs) is presented in this paper. LTDA-MAC provides collision free scheduling of packet transmissions in underwater networks. The purpose of this paper is to explore the use of LTDA-MAC in linear chain underwater acoustic networks comprising nodes with full-duplex capability, and show the performance gains that can be achieved through improved temporal re-use of an acoustic channel. Simulation results show that more efficient packet scheduling can be achieved for full-duplex scenarios compared with half-duplex scenarios, to provide higher monitoring rates for long range underwater pipelines given low cost, mid range, low rate and low power acoustic modems. This study shows the benefits that could be achieved from the LTDA-MAC protocol simply by switching on the full-duplex capabilities without having to change the protocol.**

***Index Terms*—Medium access control, full-duplex, relay, underwater.**

I. Introduction

Underwater Acoustic Networks (UANs) have recently gained widespread attention as a result of technological breakthroughs in sensor technology, vehicular technology and underwater communication [1]. As a result, there is a lot of potential for many important applications such as oceanographic exploration including marine life and archaeological studies, and marine search and rescue missions [1]–[5]. They also have potential for improved offshore petroleum exploration, monitoring and control of underwater pipelines, border and military operations, fish farming, freshwater reservoir management, and tsunami and sea quake early warning systems [1]–[5].

Establishing communication among nodes underwater is a challenging task because of the complicated underwater channel characteristics [4], [6]–[8]. More importantly, Medium Access Control (MAC) becomes very difficult due to long propagation delays and low available bandwidth [2], [9]. As a result, designing a (MAC) protocol for UANs in the presence of the aforementioned underwater channel characteristics is difficult and traditional approaches are either unsuitable or provide poor throughput, high latency and low energy efficiency.

Various MAC protocols that operate in a half-duplex fashion have been developed in order to improve network performance in UANs. These protocols are either scheduling based such as: Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA) and Space Division Multiple Access (SDMA); or contention based utilising carrier sensing, handshaking or random access techniques [10].

However, problems of QoS (Quality of Service) and energy efficiency still persist mainly due to long propagation delays and limited available bandwidth in the underwater channel [11]. These network performance problems become more evident in multi-hop UANs. Time-based synchronization schemes may be an option for short term applications, however, maintaining synchronization for long term applications in underwater networks is quite challenging and may incur significant overheads and thus, makes time-based access techniques less viable for long term applications in multi-hop underwater acoustic networks. In the same vain, long propagation delays also create some uncertainty around channel idle/busy status prediction, which reduces the effectiveness of carrier sense protocols in UANs and this is amplified in multi-hop UANs. Additionally, handshaking techniques such as Request-To-Send/Clear-To-Send (RTS/CTS) based protocols [12]–[15] are also highly impacted by long propagation delay among other issues such as low scalability and robustness, thereby, challenging their suitability for multi-hop UANs. The LTDA-MAC protocol has been designed to provide better network performance and efficiency by optimising packet scheduling in linear UASN-based pipeline monitoring systems without clock synchronization at the sensor nodes [16], [17].

Recent advances in self-interference cancellation in in-band full-duplex communication (a phenomenon whereby network nodes can transmit and receive data packets simultaneously within the same frequency bandwidth) is bringing about a new opportunity for improving spectral use and throughput in acoustic communication systems [18], [19]. Interestingly, this can solve some of the MAC layer problems by potentially improving network performance in terms of providing higher throughput, low latency, and by providing an opportunity for a node to simultaneously sense the channel while receiving a packet. [20]–[22].

The LTDA-MAC protocol is designed to generate efficient packet schedules devoid of collisions with significantly shorter frame duration. However, the LTDA-MAC can leverage full-duplex communications (simultaneous transmission and reception in some of the nodes within the chain network) which enhance simultaneous packet scheduling in the network to achieve collision-free packet schedules with almost half the frame duration compared to the half-duplex case. This significantly enhances spatial spectrum reuse, especially in the long range pipeline scenarios.

Thus, the purpose of this paper is to investigate the potential performance gains to be achieved in full-duplex network scenarios using LTDA-MAC protocol. This follows on from [16] and [17] which apply the LTDA-MAC to a half-duplex based line underwater network. Consequently, this can allow simultaneous transmission and reception and thereby enhance efficient packet scheduling to achieve high monitoring rates over long range underwater pipelines using low cost, mid range, low rate and low power acoustic modems such as the such as those presented in [23]. This study also shows the benefits that can be achieved from the LTDA-MAC protocol simply by switching on the full-duplex capabilities without having to change the protocol. Additionally, this study investigates the merits of a multi-hop relay network to improve network coverage and bandwidth usage especially for long range applications such as underwater oil and gas pipeline monitoring. This study is based on simulation and BELLHOP [24] based underwater channel characterisation.

The remainder of this work is organised as follows. Section II provides an overview of the LTDA-MAC protocols, while, the operation of the LTDA-MAC in UANs in the Full-Duplex (FD) mode is presented in section III. Section IV presents the simulation set-up and the performance evaluation of the LTDA-MAC in FD scenarios is given in Section V. Conclusion are provided in Section VI.

II. LTDMA-MAC

As the focus of our study is on the performance of the LTDA-MAC protocol in a network with full-duplex enabled communication nodes, a brief review of two versions of the protocol is presented. LTDA-MAC is a protocol that utilises packet schedule optimization for UASN devoid of the need to synchronize sensor node clocks. On line optimization must derive short frame duration and short packet delays to avoid collisions at the nodes. LTDA-MAC schedules packet transmission times based on delays accrued at nodes as the time difference between a request (REQ) packet and transmission of data packets.

Two communication steps are defined for the LTDA-MAC operation. The first step involves the transmission of a data packet from a node (acting as a source node) up the chain after receiving a REQ packet, while, at the second step, a node (acting as a relay) forwards a data packet up the chain after receiving a data packet from a node further down the chain. The transmit delays introduced due to the first and the second steps define the LTDA-MAC schedules.

The earlier version of LTDA-MAC [16] uses a Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) to jointly find good sub-optimal packet schedules for transmissions. Furthermore, an improved version of LTDA-MAC is presented in [17] which uses a greedy optimization algorithm. The later version shows a significantly improved packet schedules with shorter frame durations and lower computational cost.

A. Network Structure

LTDA-MAC has been evaluated for a Half-Duplex (HD) based Linear Underwater Acoustic Sensor Network (LUASN) topology in [16] and [17]. The network has a one-hop interference range and can be simplified as shown in Fig. 1.

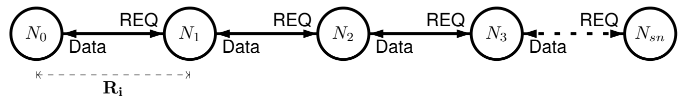


Fig. 1: Linear chain UASN.

The network comprises N_{sn} half-duplex sensor nodes (relay sensor nodes plus a master node N_0) deployed linearly as (N_0, N_1, N_2, N_3, ... N_{sn}) having an interfering range of R_i as depicted in Fig. 1. The principle operation of LTDA-MAC scheduling is summarised in Fig. 2.

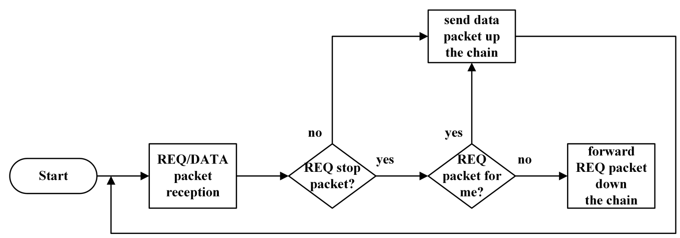


Fig. 2: LTDA-MAC network node operation.

B. Optimization process

Given that the LTDA-MAC version presented in [17] has shown a significant improvement in performance compared to its predecessor presented in [16], it is pertinent to consider and describe the improved version here. The greedy optimization algorithm proposed in [17] produces a good sub-optimal solution for packet schedules by iterating over each transmit delay in transmit delay space (a triangular matrix of transmit delays, $\boldsymbol{T_{tx}}$). The two communication steps described in Section II are defined as constraints imposed on the transmit delays.

Consider a node, N_i, acting as a source node sending its own data packet up the chain after receiving a REQ packet with a transmit delay $T_{tx}[i,i]$. The node acting as a relay node receiving a data packet from a node, N_j down the chain and forwarding it up the chain has a transmit delay $T_{tx}[i,j]$ (i.e $i < j$). The optimization algorithm uses interference and propagation delays conditions to find a good sub-optimal solution for $N_{sn}(N_{sn}+1)/2$ in $\boldsymbol{T_{tx}}$ as the minimum frame duration. As detailed in [17], the minimum frame duration is given as min $\tau_{\text{frame}}(\mathcal{N}, \boldsymbol{T_{tx}})$ (the turn around time of sending the initial REQ packet and receiving the final data packet by the sink node) in the presence of zero packet collisions, $\eta_{col}(\mathcal{N}, \boldsymbol{T_{tx}}, \tau_g)$, where, $\mathcal{N}$ and τ_g denote a given network topology and guard time, respectively. The minimum transmit delay, $T_m[n,n]$ for the first and second communication steps are given in [17] as:

$$\forall n \in \{1..N_{sn}\}\,,\; T_m[n,n] = \begin{cases} \tau_{rp} + 2\tau_g, & n < N_{sn} \\ \tau_g, & n = N_{sn} \end{cases}, \quad (1)$$

and

$$\forall n, k \in \{1..N_{sn}\}\,, k > n,$$
$$T_m[n,k] = 2(\tau_p[n+1] + \tau_g) + \tau_{rp} + \tau_{dp} + T_{tx}[n+1,k], \quad (2)$$

where τ_{rp} represents the REQ packet duration, τ_{dp} denotes the data packet duration, τ_g is the guard time, $\tau_p[i]$ is the propagation delay on the link between the i^{th} and $i+1^{th}$ nodes and $T_{tx}[n+1,k]$ is the transmit delay between $(n+1)^t h$ receiving a REQ packet and transmitting the data generated by node k.

The packet collision term, $\eta_{col}(\mathcal{N}, \boldsymbol{T_{tx}}, \tau_g)$, is calculated using the transmit and receive times of each packet in a frame. Hence, for the HD case, any overlap in a pair of transmit/receive packets at the same node signals a packet collision and increases the value of $\eta_{col}(\mathcal{N}, \boldsymbol{T_{tx}}, \tau_g)$ by 1. However, the above collision rule is relaxed for the case of FD and so transmit/receive packets overlapping in time at the same node are not counted as collisions and in this case $\eta_{col}(\mathcal{N}, \boldsymbol{T_{tx}}, \tau_g)$ is not incremented. More information on the derivation of (1) and (2) can be found in [17].

III. LTDA-MAC in Full-Duplex Scenarios

The description of the full-duplex network topologies used to investigate the performance of the LTDA-MAC protocol is presented here. The linear chain network topology is retained but the nodes are able to operate in full-duplex fashion rather than half-duplex. Fig. 3 depicts full-duplex communication in a linear underwater chain network, and it also follows the same network operation as summarised in Fig. 2, only that the relay nodes are able to transmit and receive simultaneously in time and frequency. This allows the nodes to send and receive REQ or data packets in-band thereby potentially improving LTDA-MAC schedules unlike the HD topology in Fig. 1 where sending and reception of REQ or data packets cannot happen at the same time within the same band.

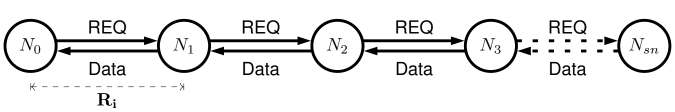
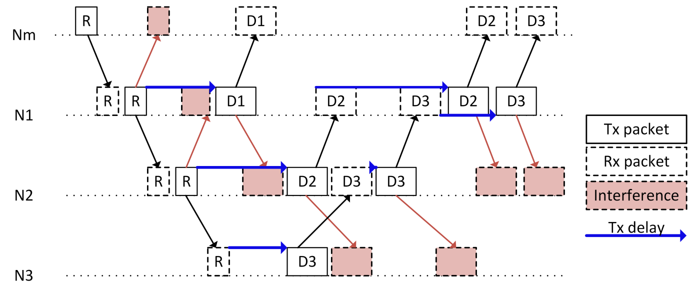


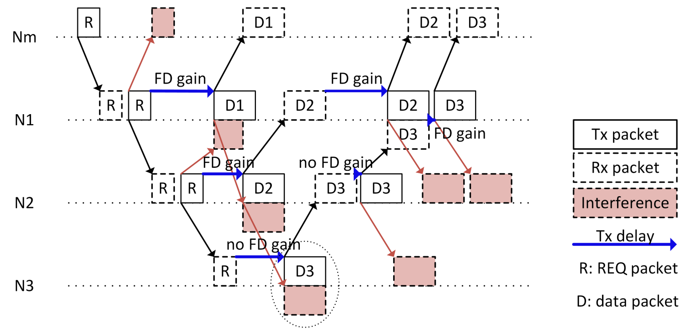
Fig. 3: FD-based LUASN network scenario.

Considering a one-hop interference range example, the corresponding LTDA-MAC schedule is depicted in Fig. 4.

Comparing the frame length in full-duplex scenario depicted in Fig. 4(b) to that in half-duplex scenario shown in Fig. 4(a), it can be observed that a significant reduction in frame length is possible with full-duplex scenario. This is because, in Full-duplex case, overlap between packet transmission and reception in a node is possible and thus, reduce the frame duration that is accounted for as the FD gain in Fig 4(b).



(a) HD network scenario [17]



(b) FD network scenario

Fig. 4: Typical LTDA-MAC schedules in three-hop network.

Transmit delay is a major parameter of packet scheduling in LTDA-MAC as shown in [16] and [17]. The good sub-optimal solution produces a minimum transmit delay thereby producing the shortest possible frame duration. For any node N_i to transmit its own data packet up the chain and to forward a REQ packet down the chain, the minimum transmit delay, $T_m[n,n]$ to be ensured as modified from (1) to account for full-duplex operation is:

$$\forall n \in \{1..N_{sn}\}\,,\; T_m[n,n] = \begin{cases} \tau_{rp} + \tau_g, & n < N_{sn} \\ \tau_g, & n = N_{sn} \end{cases}. \quad (3)$$

Comparing (3) with (1), we can see that a transmit delay reduction that is proportional to a half of the guard time could be saved in this operation compared to the HD case and this further explains the transmit delay gain obtainable for the topology shown in Fig. 4(b).

IV. Performance of LTDA-MAC in FD scenarios

A. Simulation set-up

The simulation procedure used to evaluate the performance of LTDA-MAC for full-duplex pipeline monitoring scenarios is described here. The scenarios are categorised as small, medium and large scale in accordance with the pipeline lengths. In each of the scenarios, the maximum sea depth is considered to be 500 m. The pipeline is deployed at 480 m which is then connected through a riser to the platform as described in [17]. The nodes are deployed in the pipeline in a chain fashion as multi-hop nodes consisting of a master (or sink) node and relay nodes that transmit packets down or up the chain as required. Different configurations of the scenarios are described in Table I. The intention is to provide an evaluation of the scheduling benefits of LTDA-MAC with full duplex nodes for any conceivable chain network length, ranging from very small networks with few nodes to long pipelines comprising many nodes. For all the scenarios, sensor nodes are spread across the length of the pipeline at equidistant points of 1 km / 2 km taking into account the capabilities of the considered acoustic modem with 1 km being a reliable range and 2 km approaching the range limit. We focus on this particular modem and its range capability due to its low cost which makes it feasible to consider deploying large number of monitoring devices. A further benefit of considering relatively short range acoustic communication is the provision of regular monitoring points for the detection of problems such as leaks and movement of pipelines. In furtherance, the BELLHOP beam tracing method described in [25] is used to generate the statistical underwater channel characterization for the considered cases. A wide range of parameters based on the features of acoustic nano modems are considered. The key modem and channel parameters are shown in Table 1.

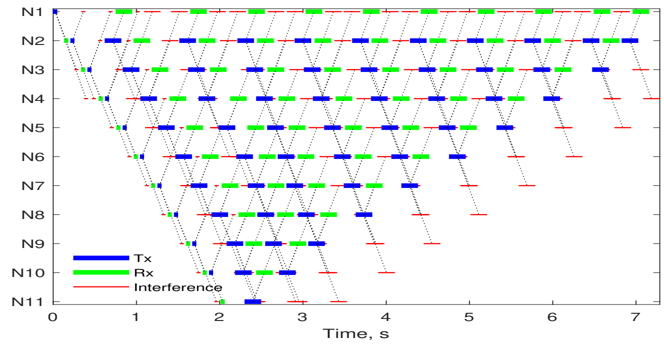
TABLE I: Simulation Parameters

Parameter	**Value**
Transmit power (Small scale scenarios)	140 dB re μ Pa^{2}m^2
Transmit power (Medium and large scale)	170 dB re μ Pa^{2}m^2
τ_{dp} (Small/Medium and Large scale)	200 ms / 500 ms
τ_{rp} (Small/Medium and Large scale)	50 ms / 100 ms
τ_g (Small/Medium and Large scale)	25 ms / 100 ms
Acoustic modem range Centre frequency/Bandwidth	1 km / 2 km 24 kHz / 7.2 kHz
Shipping activity factor	0.5
Wind speed	10 m/s
Interfering link detection threshold	0 dB SNR
Sound speed Profile	North Atlantic Ocean SSP
Pipeline length (L)	2 km to 1000 km
Number of hops (H)	2 to 1000 hops
Scenario	***Description***
Small_L_H	Small scale scenario
Medium_L_H	Medium scale scenario
Large_L_H	Large scale scenario

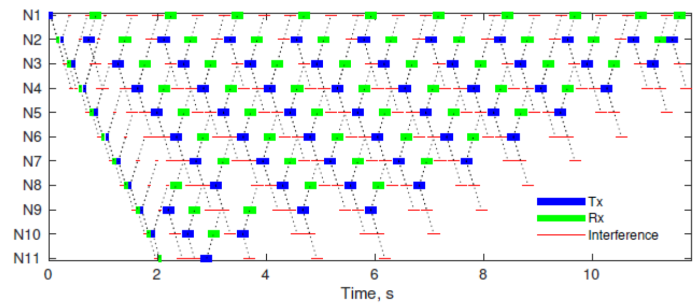
B. Simulation results and discussion

Figure 5 shows simulated LTDA-MAC schedules for both HD and FD network scenarios for a 10-hop 2 km pipeline. As can be seen from Fig. 5(a), packets are correctly received at the desired destination nodes despite the overlap in time between the transmit and interference packets. The correct reception of packets in the presence of overlap in time is made possible as result of the simultaneous transmit and receive capability of full-duplex communication, this is in contrast with Fig. 5(b) which does not allow in-band transmission. As a result, frame durations and end-to-end mean packet delays are shorter in the FD scenario compared to the HD scenario. The implication of this significant improvement is discussed as follows.

Results presented here consider short pipelines of few kilometres to longer pipelines of several thousands kilometres.



(a) FD case



(b) HD case [16]

Fig. 5: Simulated LTDA-MAC schedules for 2 km 10-hop scenario.

Short pipelines are considered in order to understand the benefits of full-duplex communication in simple situations where there is a limited opportunity and requirement for spatial re-use. The longer pipelines correspond to underwater oil and gas pipeline monitoring systems that in many cases span thousands of kilometres such as the Langeled pipeline in the North Sea measuring about 1,200 km [26], and the 7,200 km long pipelines under the gulf of Mexico [27]. We present the frame durations for the scenarios as shown in Figs. 6 and 7. Frame duration is important because it defines the frequency with which each node can send a new sensor reading. The small scale scenario results as seen in Fig. 6 shows that the frame durations derived for the full-duplex cases are significantly shorter than those derived for the half-duplex ones. Hence, this capability provides better packet schedules which translates to a significant improvement in network throughput.

Applications such as leak detection require timely sensor readings at certain intervals and demand a high resolution of sensed data. The results of HD cases especially for the longer pipelines (50 km and 100 km) shown in Fig. 7 show that high monitoring rates cannot be achieved, with intervals of about 3000 and 4500 seconds respectively per sensor node. This may be too long for some applications that require more frequent sensor reading(s), however, the corresponding results of the FD cases show that the monitoring interval per sensor node is reduced to about 800 seconds at maximum. Hence, the monitoring rate could be significantly increased with full duplex nodes to more than five times the corresponding half duplex case based on use of an acoustic modem with a 1 km sensing range.

Furthermore, for sensing applications that require regular sensing along a pipeline but higher monitoring rates, more regular monitoring can be achieved by employing acoustic modems with a 2 km sensing range. From Fig. 7, it can be seen that monitoring interval per sensor node is further reduced to about 200 and 150 seconds for the 50 km and 100 km pipelines respectively.

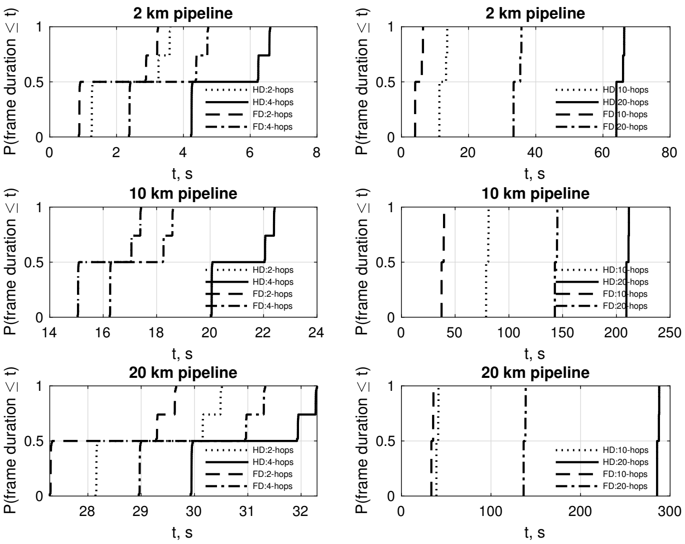


Fig. 6: LTDA-MAC packet schedules in HD versus FD for small scale scenarios.

The significant performance improvement achieved with the medium scale scenarios compared with small scale scenarios suggests that the LTDA-MAC algorithm utilises full-duplex communication capabilities better in a more dense scenarios.

For the large scale network scenarios which consist of pipelines with lengths 200 km, 500 km and 1000 km, a hierarchical approach can be employed using LTDA-MAC in 10 - 100 km segments. The monitoring intervals here may be very long as can be seen in Table II for the HD 1000 km pipeline case requiring up to 8000 seconds which may be impractical for many pipeline monitoring applications. Providing more regular monitoring for these longer pipeline scenarios may require high power and longer range costly acoustic modems, however, FD based scenarios configured with 2 km sensing range acoustic modems could relatively reduce the monitoring rate to acceptable values such as 553 seconds for a 500-hop 1000 km pipeline scenario. It is thus important to state that although longer range acoustic modems could be employed to achieve higher monitoring rates across a lower numbers of hops (the number of sensor nodes required), the cost effectiveness of nano modems provides a relatively cheaper alternative and along with FD communication can achieve an acceptable monitoring rate whilst maintaining more regular sensing points along a pipeline. The mean frame duration and end-to-end packet delays derived for the large scale scenarios are given in Table II.

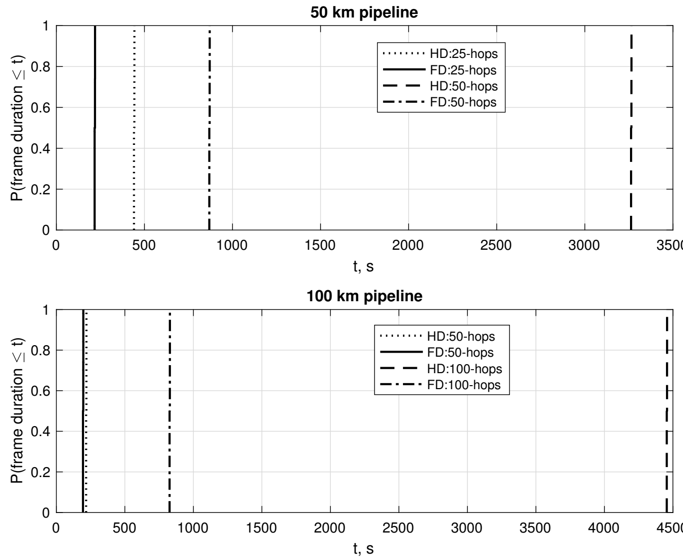


Fig. 7: LTDA-MAC packet schedules for medium scale pipeline scenarios.

TABLE II: Mean values of frame duration and end-to-end packet delay

Pipeline(km)	hop	Frame duration(s)		E2E packet delay(s)	
		HD	***FD***	***HD***	***FD***
200	100	606.6	297.8	400.4	193.7
	200	4456.7	1255.6	2326.1	875.8
500	250	828.2	405.8	544.8	262.5
	500	6084.7	1619.8	4526.0	1128.8
1000	500	1130.7	552.7	743.8	364.7
	1000	8307.4	2795.6.0	6179.4	1790.0

V. Conclusions

A performance evaluation of the LTDA-MAC protocol over full-duplex underwater acoustic chain network scenarios has been presented. The paper investigated the network performance benefits to be had from the application of the 'Greedy' optimization based LTDA-MAC protocol on full-duplex underwater pipeline network monitoring scenarios. Advantage of spectrum re-usability of LTDA-MAC is leveraged by the full-duplex communication mechanisms to exploit long propagation delay and interference patterns to provide a more efficient packet schedules, which in turn provides greater network throughput performance in the studied scenarios. Results that are based on simulation of small scale (2 km, 10 km and 20 km), medium scale (50 km and 100 km) and large scale (200 km, 500 km and 1000 km) scenarios show that a significant performance enhancement is achieved by the application of LTDA-MAC protocols to full-duplex pipeline monitoring scenarios with respect to their half duplex counterparts. A key endeavour in the future will be to integrate full-duplex communication mechanisms in LTDA-MAC to further enhance network performance and also to test how reinforcement learning optimization of the scheduling algorithm performs against 'Greedy' optimization algorithm.

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